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Research report

Behavioral and electrophysiological effects of task-irrelevant sound change: a new distraction paradigm

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Abstract

A distraction paradigm was utilized that is suited to yield reliable auditory distraction on an individual level even with rather small frequency deviances (7%). Distraction to these tiny deviants was achieved by embedding task-relevant aspects and task-irrelevant, distracting aspects of stimulation into the same perceptual object. Event-related potential (ERP) and behavioral effects of this newly developed paradigm were determined. Subjects received tones that could be of short or long duration equiprobably. They were instructed to press a response button to long-duration tones (targets). In oddball blocks, tones could be of standard frequency or of low-probability ($p = 0.1$), deviant frequency. The task-irrelevant frequency deviants elicited MMN, N2b, and P3a components, and caused impoverished behavioral performance to targets. The usage of tiny distractors permits an interpretation of auditory distraction in terms of attention switching due to a particular memory-related change-detection process. On the basis of the results from an additional condition in which tones were of 10 different frequencies (involving those frequencies which served as standard and deviant in oddball blocks), it is argued that one important prerequisite for linking the neural mechanisms reflected in change-related brain waves to behavioral distraction effects may be regarded as fulfilled. The robustness of the distraction effects to tiny deviations was confirmed in two control experiments.

Keywords: Audition; Event-related brain potential; Mismatch negativity; Distraction; Involuntary attention

1. Introduction

Unexpected, irregular sounds occurring in our acoustic environment may impair the processing of task-relevant stimulus information. This phenomenon of auditory distraction has been investigated in numerous experiments in which behavioral performance to target stimuli preceded by task-irrelevant deviant or novel events has been found to be deteriorated relative to performance to target stimuli embedded within the standard acoustic background [4,10,13,14,20,45,55,68,70,71]. The detrimental effects of task-irrelevant novels or deviants on task performance are assumed to reflect the result of attentional orienting towards the perturbating sound.

Recent research was aimed at determining the mechanisms underlying auditory distraction by combining behavioral and event-related potential (ERP) measures (e.g., Refs. [4,13,55,70]). Likely candidates that might mediate behavioral distraction effects caused by unexpected deviant sounds are the Mismatch Negativity (MMN) [43] and the P3a [61] components of the ERP which may be elicited by unattended deviant or novel sounds. The neural processes underlying these brain waves are assumed to play an important role in involuntary attention switching, which, in turn, may lead to behavioral impairment in the primary task (see, e.g., Refs. [41,55,68]). MMN is elicited by an irregularity in discrete, repetitive auditory stimulation, reveals a frontocentral distribution, and usually peaks between 100 and 250 ms from the onset of the deviation. P3a is elicited by large deviant or novel sounds, also reveals a frontocentral distribution, and peaks between 250 and 500 ms relative to stimulus onset. MMN is assumed to indicate that a deviance has been detected by the auditory system on a preattentive level of processing, whereas P3a is assumed to reflect an attentional orienting towards the perturbating event [41].

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The combination of behavioral and ERP data provides a promising approach for studying mechanisms of auditory distraction, since the output of the system visible on a behavioral level can (one hopes) be explained as the result of a series of processing stages tapped by ERP measures [57]. However, there are also several issues that have to be resolved before deviance-related ERP effects can successfully be related to behavioral distraction effects. The present experiment addresses two of these issues: (1) the question of how the theoretical interpretation of behavioral distraction depends on the type of deviance employed; (2) the question of whether distraction effects on a behavioral level relate to the same phenomenon as deviance-related effects on an electrophysiological level.

1.1. How does the theoretical interpretation of distraction depend on the type of deviance?

One issue to be discussed in this section relates to the usage of large amounts of physical differences between the acoustic background and the deviant sound (i.e., novel or large deviant) when studying distraction. Another issue relates to the usage of familiar or meaningful distractors such as dog barking. On the one hand, the usage of large deviants helps to obtain distinct behavioral distraction effects [13,70] and deviance-related ERP effects, that is, MMN and P3a [15,52]. On the other hand, the usage of large deviants creates a disadvantage from a theoretical point of view, since orienting and, as a consequence, distraction, may be due to two different mechanisms detecting the deviance: (1) a 'new-afferent-elements-activation' mechanism being able to detect salient deviants via a differential state of refractoriness of afferent elements specifically responding to the infrequently presented deviant sound and those specifically responding to the frequently presented standard sound; (2) a purely 'memory-related' mismatch mechanism being able to detect irregular events in repetitive stimulation via a memory comparison process between the representation of the actual stimulus information and a representation of the invariances inherent to the recent stimulation [41,48,57,60]. According to a model proposed by Näätänen [40], the former mechanism is reflected in the supratemporal N1 and partly in the nonspecific N1 component, and the latter mechanism is reflected in the MMN (see also Ref. [53]). It should be mentioned that also the 'new-afferent-elements-activation' mechanism may be related to memory functions (e.g., Refs. [33,34,42,64]), since refractory neurons do indirectly contain information about previous stimulation; for example, the habituation effect of N1 can be seen as a simple form of learning. However, in contrast to the memory-related change-detection mechanism, no explicit or specific memory representations are necessarily involved in the 'afferent-elements-activation' mechanism, which may therefore be regarded as less memory-related. This is indicated by the fact that the N1 can be elicited by the first stimulus in an experimental session (without recurrence to a previous standard sound), whereas the elicitation of MMN requires a memory trace of the standard sound [65]. A paradigmatic case for the less memory-related mechanism (i.e., the 'new-afferent-elements-activation' mechanism) creates the detection of a sudden, intense sound, and a paradigmatic case for memory-related change-detection, the detection of an occasional exchange of two elements in a repetitively presented tonal pattern [66], or the omission of an expected sound [72]. The contribution of each of these mechanisms to the behavioral distraction effect can hardly be disentangled with large deviants.

Moreover, attentional orienting may not only be elicited via change-detection mechanisms but also according to a match mechanism. That is, meaningful events (such as one's own name or the barking of a dog) may have attention-capturing properties per se. One may consider situations in which one's own name spoken by an unattended speaker immediately attracted our attention. The finding that dishabituation of the electrodermal orienting response [59] is more frequent for approaching than for retreating targets [6] suggests that the distraction potential of a stimulus depends on its meaning (for a converse result see [17]). A first ERP indication for the hypothesis that novelty effects are modulated by the familiarity of distractors has recently been reported by Mecklinger et al. [36]. Since meaningful novels do often also represent large deviants, distraction effects obtained with novels cannot be interpreted unequivocally with regard to the underlying attention switching mechanism. That is, distraction effects with novels such as dog-barking may be due to any or all of the three mechanisms. Therefore, in order to study auditory distraction that is caused by the memory-related change-detection mechanism small changes should be employed. However, with small changes, behavioral distraction effects are difficult to obtain and P3a (an ERP index of attentional orienting) may not be elicited in the usual distraction paradigms.

To avoid the uncertainty with respect to mechanism responsible for the distraction effect, a new paradigm was developed suited to yield reliable distraction effects with a rather small difference between standard and deviant sounds. In typical distraction paradigms, task-irrelevant and task-relevant aspects of stimulation are embedded in different objects or even in different modalities. However, a large 'channel-separation' may prevent distraction effects to occur with small distractors. According to Näätänen's attention switch model [41], conscious deviant detection can be explained as the result of a pre-attentively operating deviant detection system generating interrupt signals that have to surpass a variable threshold in order to elicit an attention switch or to get access to consciousness. The probability for exceeding this threshold is a function of (a) the attentional load of the primary task and (b) of the channel-separation of task-relevant and task-irrelevant aspects of stimulation [9,57]. That is, distractors that are physically similar to the targets should produce more interference because they fall within the attentional filter, and therefore are selected for further processing; whereas distractors highly distinguishable from the targets are easily dismissed since they fall outside the filter.

The influence of channel-separation may explain some puzzling results obtained in auditory distraction experiments. For example, in an experiment reported by Alho et al. [4], subjects were presented with mixed sequences of equiprobable auditory and visual standard stimuli which were randomly interspersed with two kinds of deviants one of them being a target stimulus requiring an overt response, the other being a task-irrelevant deviant. Behavioral performance to these target stimuli was impaired when preceded by a task-irrelevant deviant of the same modality compared to target performance to a target preceded by a standard. However, deviants in the unattended modality did not affect the behavioral response to targets. A similar absence of intermodal distraction effects has been observed in a study by Woods et al. [69]. That is, no intermodal distraction effects did occur but distinct intramodal distraction effects, in which task-relevant and task-irrelevant aspects of stimulation were more similar. Since the attentional load was presumably similar in both conditions, that absence of inter-modal distraction can be explained as a consequence of the increase in channel-separation between task-relevant and task-irrelevant aspects of stimulation.

It is known from the visual domain that distractors are more effective if target and distractor are embedded in the same object or perceptual group than if the distractor is located in a different object [5,11,30]. Corresponding effects have been reported for the auditory modality, where behavioral distraction effects [1,8,26] and ERP attention effects [2] were found to depend on the clustering of the acoustic input into auditory objects. This means that larger distraction effects (even to small deviations) can be expected if the stimulus dimension carrying task-relevant information and the stimulus dimension on which deviations can occur are located in the same auditory object than when they belong to different objects. In the present paper, a new paradigm will be presented in which the task-relevant stimulus dimension was orthogonally crossed with the task-irrelevant dimension. The task-relevant dimension was duration and the task-irrelevant dimension was frequency; short and long duration tones were presented equiprobably, and subjects had to press a button to long duration stimuli; within the task-irrelevant dimension, tones could be of standard ($p = 0.9$) or of deviant frequency ($p = 0.1$). However, unlike with usual auditory distraction paradigms, distractors (i.e., tones being of deviant frequency) did require a response with the same probability than did non-distractors (i.e., tones being of standard frequency; Fig. 1). It was predicted that distinct behavioral distraction effects will be obtained with this paradigm, since one and the same perceptual object carries

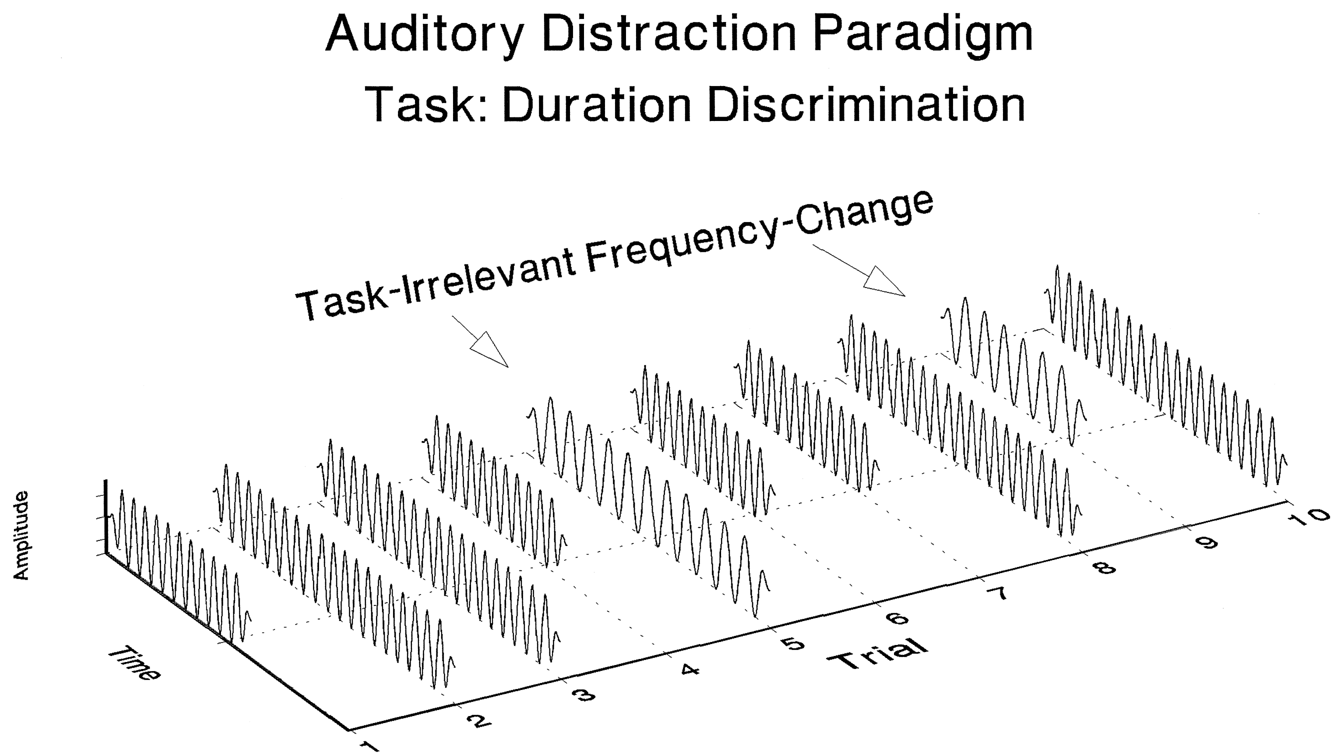


Fig. 1. Illustration of the distraction paradigm with the task-relevant stimulus dimension being duration (equiprobably presented short and long duration tones), and the task-irrelevant stimulus dimension being frequency (including a frequent standard and an infrequent deviant frequency). Subjects had to discriminate between short and long duration stimuli.

task-relevant information that differentiates targets from non-targets, as well as presumably distracting information about a task-irrelevant deviance. In other words, channel-separation between task-relevant and task-irrelevant aspects of stimulation is minimized and, as a consequence, distraction effects are expected.

1.2. ‘Cost-benefit’ decomposition of auditory distraction

A second issue that is addressed in this paper concerns an untested assumption when relating deviance-related ERP effects to behavioral distraction effects, that is, the assumption that distraction effects on a behavioral level relate to the same phenomenon as deviance-related effects on an electrophysiological level. Distraction effects are usually defined as the difference in behavioral performance to targets preceded by a task-irrelevant deviant and to targets preceded by a task-irrelevant standard. However, a particular difference in this comparison could be produced by two different, logically equivalent alternatives; that is, it can be due to a modulation in the processing of deviant-preceded targets or due to a modulation in the processing of standard-preceded targets. According to the cost–benefit technique applied in behavioral research on selective attention, the former may be termed ‘costs’ and the latter ‘benefits’ [50]. Although the existence of benefits does not seem to be very plausible in the case of auditory distraction, they cannot be ruled out completely. One may, for example, consider that a task-irrelevant homogeneous auditory background may possibly lead to a superior arousal level resulting in improved behavioral performance (e.g., Ref. [51]). If the behavioral distraction effects only consist of benefits, the observed deviance-related ERP effects (i.e., MMN and P3a) cannot directly be linked to the distraction effects, since MMN and P3a are due to a modulation in the processing of deviants (e.g., Ref. [40]).

In order to test whether behavioral distraction is (at least partly) due to costs in the processing of deviant-preceded targets, not only oddball blocks containing deviants and standards were run, but also control blocks were included in the main experiment (Table 1). This condition was designed to permit to determine the minimal amount of costs being visible in the difference in behavioral performance to deviant-preceded and to standard-preceded targets. In these control blocks, the stimulus dimension in which deviants differed from standards in oddball blocks (i.e., frequency) was varied over a large scale of different values. That is, there were no standards and deviants but a random variation of different frequencies. By comparing the behavioral performance to targets being of deviant frequency (presented in oddball blocks) with the behavioral performance to physically identical stimuli presented in control blocks, it should be determined whether distraction effects are due to costs, benefits, or both.

In sum, the present study determined the effects of a newly developed distraction paradigm on a behavioral and on an electrophysiological level. To evaluate the efficiency of deviant events in eliciting distraction, the amount of the physical difference between standard and deviant was varied in three steps by employing small, medium, and large deviants. Furthermore, in order to test the unverified assumption of research relating behavioral distraction effects to deviance-related ERP effects (i.e., the assumption that distraction effects reflect a modulation in the processing of deviance-preceded targets), a ‘cost-benefit’ analysis of the distraction effects was performed. Finally, two additional control experiments were performed to replicate the distraction effects to tiny deviations in task-irrelevant aspects of stimulation obtained with the new auditory distraction paradigm. In these control experiments, we varied target probability, response requirement, and tone duration in order to evaluate the robustness of the distraction effects.

2. Main experiment: materials and methods

2.1. Subjects

Fifteen paid healthy subjects (ages 19–36 years, mean 25.7 years; 9 males) reporting normal hearing participated in the experiment. Subjects were seated in a comfortable chair in an electrically shielded and acoustically attenuated cabin during the experiment.

Table 1
Experimental design

Condition	Stimulus-type (frequencies)	Within-block probabilities	
		Short tones (Nogo)	Long tones (Go)
Small-Deviant	Standard (700, 750)	0.45	0.45
	Deviant (750, 700)	0.05	0.05
Medium-Deviant	Standard (700, 900)	0.45	0.45
	Deviant (900, 700)	0.05	0.05
Large-Deviant	Standard (700, 1200)	0.45	0.45
	Deviant (1200, 700)	0.05	0.05
Randomly-Varying-Frequencies	Control (700, 750, 800, 850, 900, 950, 1000, 1050, 1100, 1200)	10×0.05	10×0.05

2.2. Procedure

Auditory stimuli were short (100 ms) and long (200 ms) sinusoidal tones (rise and fall times of 5 ms; intensity of 70 dB SPL) generated with NeuroScan stimulation unit. Short and long tones were presented binaurally via headphones with equal probability. Subjects were instructed to perform a button-press response with their left index-finger to long tones. There was one training block at the beginning of the experiment and nine experimental blocks each containing 300 stimuli. The constant offset-to-onset interstimulus interval (ISI) was 1 s. Within a block, tones differed in frequency. In oddball blocks, tones were either of standard frequency ($p = 0.9$) or of deviant frequency ($p = 0.1$). In three different conditions, the magnitude of the physical deviation between standards and deviants was small (50 Hz), medium (200 Hz), and large (500 Hz). These conditions are referred to as Small-Deviant, Medium-Deviant, and Large-Deviant conditions. Subjects received two blocks of each condition the difference being that the role between standard and deviant frequency was exchanged. In one block of the Small-Deviant condition, the standards were 700 Hz in frequency and the deviants 750 Hz, whereas in the second block, standards were 750 Hz in frequency and deviants 700 Hz. In the Medium-Deviant condition, the two frequencies employed were 700 Hz and 900 Hz, and in the Large-Deviant condition, the frequencies were 700 and 1200 Hz. There was an additional condition, in which tones of 10 different frequencies (700, 750, 800, 850, 900, 950, 1000 1050, 1100, 1200 Hz) were presented equiprobably. This Randomly-Varying Frequencies condition contained all those frequencies which served as deviant frequencies in the oddball blocks. Furthermore, the probability of a particular frequency (e.g., 750 Hz) was identical to the probability of this frequency in the oddball block in which it served as the deviant. However, these tones cannot be regarded as deviants, since no standards were present in the Randomly-Varying-Frequencies condition. Their role was to serve as controls for deviants from oddball blocks. If not only the Deviant minus Standard but also the Deviant minus Control comparison shows behavioral distraction, it would be demonstrated that distraction is (at least partly) due to costs. Stimulus parameters and conditions are delineated in Table 1.

2.3. EEG measurement

The EEG was measured with Ag–Ag/Cl electrodes from 10 scalp locations: Fpz, Fz, Cz, and Pz (10–20 system), both mastoids (lM and rM, respectively), two electrodes placed at 1/3 and 2/3 of the arc connecting Fz to LM (L1, L2), and homologous electrodes over the right hemisphere (R1, R2). The horizontal EOG was monitored at the outer canthus of the left eye. The reference electrode was positioned at the nose. The EEG and EOG were digitized by NeuroScan data-acquisition unit at a rate of 200 Hz and with a filter bandpass of 0.1 to 40 Hz. Epochs were 800 ms in duration (including a 100 ms prestimulus baseline). Epochs with EEG or EOG changes exceeding 150 μV were rejected from further analysis. In oddball blocks, ERPs were averaged, separately for each Amount-of-Deviance condition (Small-Deviant, Medium-Deviant, Large-Deviant) and Stimulus-Type (Standard, Deviant). In the Randomly-Varying Frequencies condition (oddball blocks), ERPs to those tones were computed, which were employed as deviants in the corresponding oddball condition. This results in three different Control-ERPs: Small-Deviant-Control-, Medium-Deviant-Control-, and Large-Deviant-Control-ERPs. Individual ERPs were low-pass filtered (25 Hz; 24 dB/octave).

2.4. Data analysis: behavioral data

Button-press responses to long stimuli in the interval from 250–1000 ms relative to stimulus onset (i.e., 150–900 ms relative to onset of the duration difference) were regarded as correct responses (hits). Button-press responses to short stimuli in the interval from 50–1000 ms were regarded as erroneous responses (false alarms). Reaction times (RTs) in correct trials, hit rates, and false alarm rates were determined separately for stimuli being of standard and deviant frequency in the three different Deviant conditions. That is, hit rates and RTs were computed from the responses to long stimuli, and false alarm rates from responses to short stimuli. In the Randomly-Varying-Frequencies condition, only tones being of the frequencies of the corresponding Small-, Medium-, and Large-Deviant conditions were taken into account. This resulted in three different Control-RTs (Small-Deviant-Control-RT, Medium-Deviant-Control-RT, and Large-Deviant-Control-RT); for example, the Small-Deviant-Control-RT is the RT to tones having a frequency of 700 Hz and 750 Hz presented in the Randomly-Varying-Frequencies condition. The values were compared with ANOVAs employing the factor Stimulus-Type (levels: Standard, Control, Deviant) and Amount-of-Deviance (levels: Small-Deviant, Medium-Deviant, Large-Deviant).

The comparison of performance between stimuli being of standard and those being of deviant frequency was used to determine behavioral distraction effects. The Deviant vs. Control and the Standard vs. Control comparisons were performed to break down the distraction effects into ‘costs’ and ‘benefits’, respectively.

2.5. Data analysis: ERP-data

To evaluate the MMN, two different kinds of difference waves were computed: First, the ‘traditional’ difference waves were formed by subtracting Standard-ERPs from Deviant-ERPs. Second, ‘modified’ difference waves were obtained by subtracting Control-ERPs from Deviant-ERPs.

The advantage of this procedure is that the MMN should be less overlapped by N1 refractoriness effects, since deviants and controls were of identical within-block probability. At least in the Large-Deviant condition, standards and deviants are physically highly different, which probably results in refractoriness of neurons being responsive to standards. An increase in negativity to Deviant-ERPs in the MMN range may then partly be a result of a release from N1 refractoriness (cf. Ref. [53]), i.e., the 'true' MMN amplitude may be overestimated in the traditional subtraction method [42,56].

MMN and N2b amplitudes were measured as the mean amplitudes in the 50-ms intervals around the latencies of the peak in the corresponding grand-average responses from Fz and from the left mastoid. Fz was chosen since MMN and N2b are most prominent at Fz. The left mastoid was chosen to differentiate between MMN and N2b (the MMN inverts polarity at the mastoids when nose reference is used whereas the N2b does not). The P3 amplitudes was measured from Fz lead, which yielded deviance-related P3 effects that were as large as those obtained at Cz and Pz (cf. Fig. 4). Component peak latencies (MMN, N2b, P3) for each subject were determined on the basis of the scalp-distribution.

The presence of the MMN, N2b, and P3 amplitudes was statistically evaluated by one-tailed one-group t-tests of the difference amplitudes, separately for the different Amount-of-Deviance conditions and subtraction methods. To compare the MMNs across the different conditions, repeated measurement analyses of variance (ANOVA) were performed employing the Amount-of-Deviance (levels: Small-Deviant, Medium-Deviant, Large-Deviant) as factor. Corresponding ANOVAs were computed with the N2b and P3 amplitudes.

3. Main experiment: results

3.1. Behavioral data: reaction times

Fig. 2 shows the RTs to long tones, separately for the factors Stimulus-Type (Standard, Control, Deviant) and Amount-of-Deviance (Small, Medium, Large). The Standard-RTs were shortest and Deviant-RTs were longest in each Amount-of-Deviance condition. In the Small-Deviant and Large-Deviant conditions, each subject showed an RT increase for deviants relative to standards; in the Medium-Deviant condition, each (except one) subject showed an RT prolongation to targets being of deviant frequency. Furthermore, the Control-RTs were prolonged as compared with the Standard-RTs and shortened as compared with the Deviant-RTs.

The omnibus-ANOVA yielded a significant main effect of Stimulus-Type ($F_{2,28} = 22.94$, $p < 0.001$, $\epsilon = 0.98$). There was also an Amount-of-Deviance main effect ($F_{2,28} = 8.22$, $p < 0.002$, $\epsilon = 0.86$) indicating that RT increased

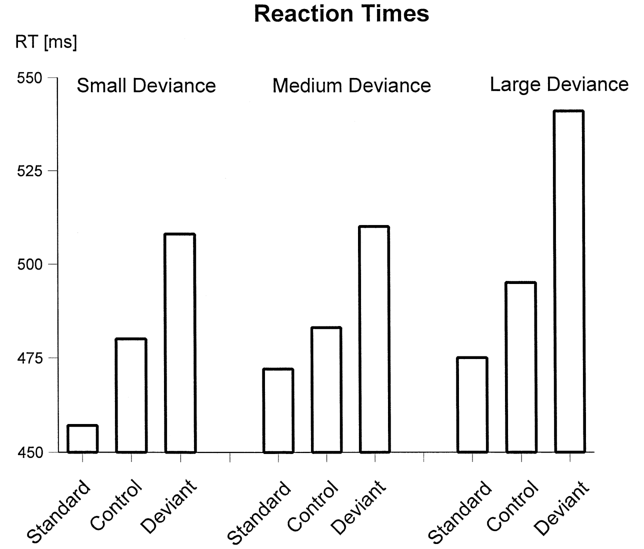


Fig. 2. Reaction times to target stimuli (i.e., long duration tones), separately for standard, control, and deviant stimuli in the Small, Medium, and Large Amount-of-Deviance conditions (main experiment).

with increasing magnitude of physical difference between the frequencies being employed. The Stimulus-Type × Amount-of-Deviance interaction was not significant ($F_{4,56} = 1.50$, $p = 0.241$, $\epsilon = 0.48$). A subsequent ANOVA with factor levels of Stimulus-Type being Standard and Control (i.e., reflecting the benefits in the processing of standards relative to controls) yielded a main effect of Stimulus-Type ($F_{1,14} = 6.23$, $p < 0.026$). The corresponding ANOVA with Control and Deviant as levels of Stimulus-Type (i.e., reflecting costs in the processing of deviants relative to controls) also yielded a significant main effect of Stimulus-Type ($F_{1,14} = 17.59$, $p < 0.001$). [1] The Amount-of-Deviance main effect was significant for the ANOVA analyzing the costs and for the ANOVA analysing the benefits ($F_{2,28} = 7.32$ and 10.54, $p < 0.001$, $\epsilon = 0.89$ and 0.72), indicating that RT increased with increasing magnitude of physical difference between the frequencies being employed.

3.2. Behavioral data: hit rates

Fig. 3 (left panel) shows the hit percentages for standards, deviants, and controls, separately for the Small-Deviant, Medium-Deviant, and Large-Deviant conditions. In general, deviants yielded smaller hit rates compared with standards and controls. In the Small-Deviant condition, 12 out of 15 subjects had a reduced hit rate in the case of deviants relative to standards; in the Medium-Deviant con-

[1] Although costs were numerically larger than benefits (34 vs. 18 ms), the ANOVA in which costs (Control RT−Standard RT) and benefits (Deviant RT−Control RT) were employed as factor levels revealed no significant difference ($F_{1,14} = 1.41$, $p = 0.255$).

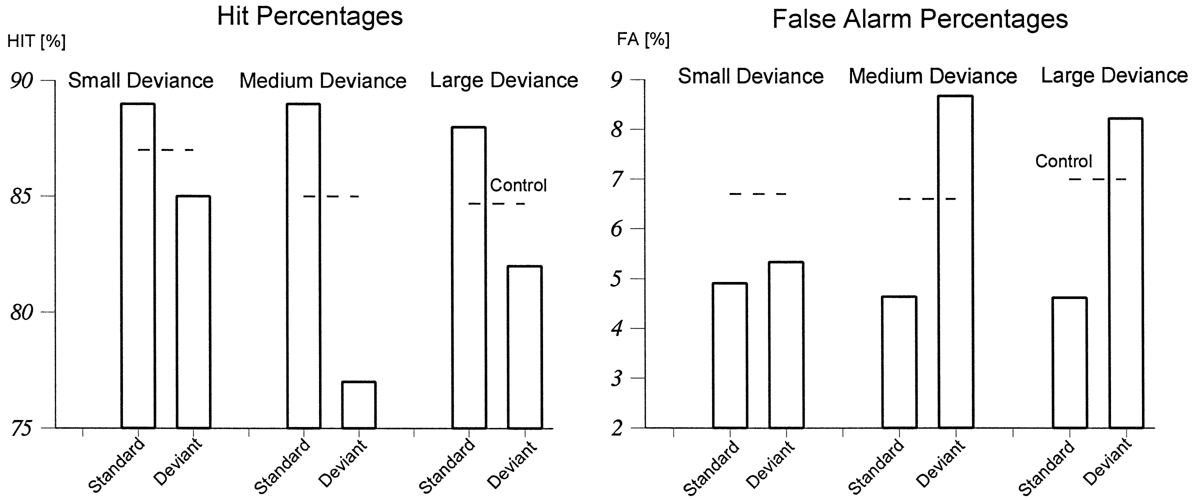
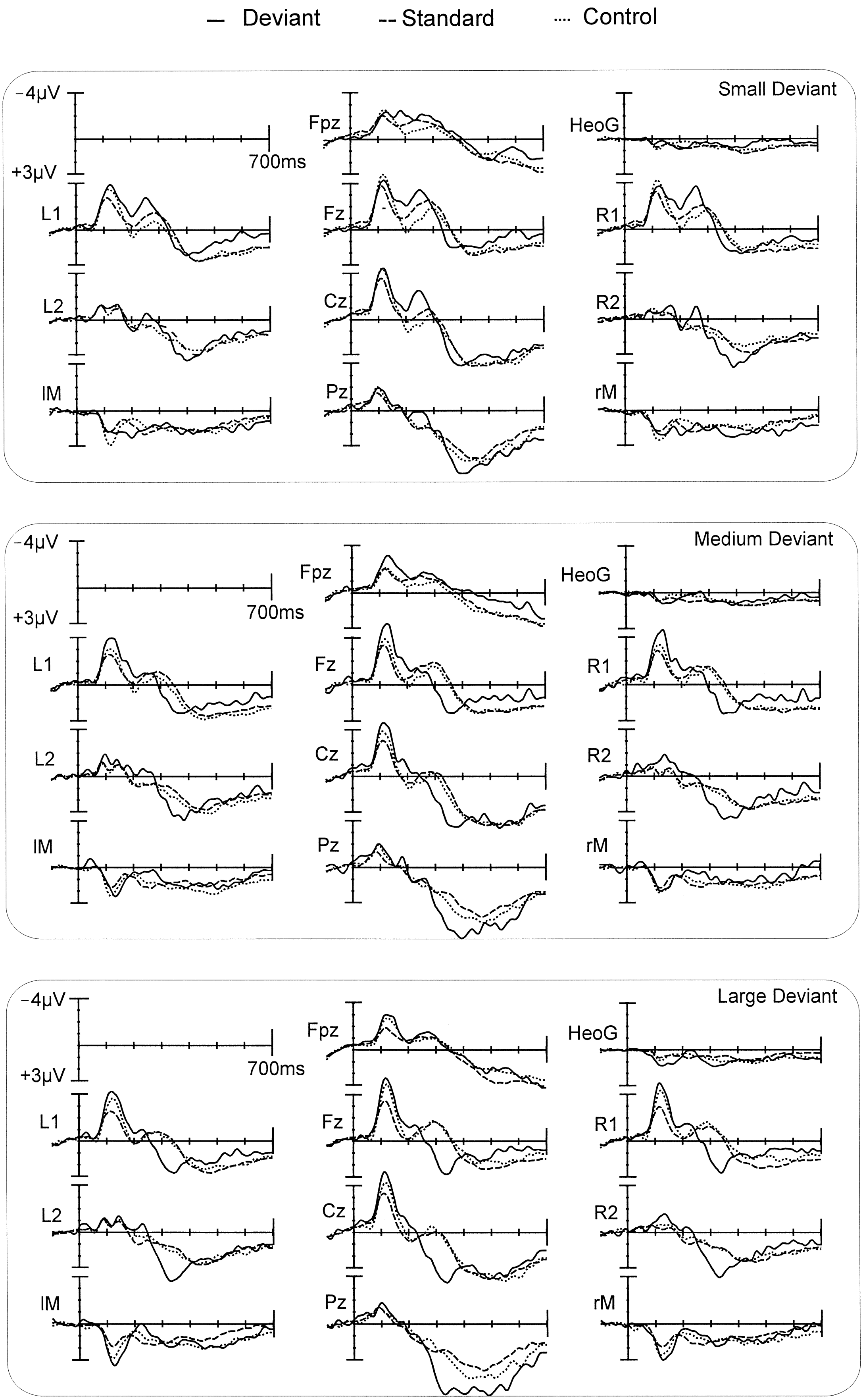


Fig. 3. Hit percentages (left panel) and false alarm percentages (right panel), separately for standard, and deviant stimuli in the different Amount-of-Deviance conditions; the values for the Control stimuli are depicted by broken lines (main experiment).

dition, 14 of the 15 subjects showed a decrease in hit rate for deviants; in the Large-Deviant condition, 11 of the subjects had a decrease in hit rate to deviants. The omnibus-ANOVA yielded a significant main effect of Stimulus-Type ($F_{2,28} = 7.82$, $p < 0.004$, $\epsilon = 0.79$). There was also an Amount-of-Deviance main effect ($F_{2,28} = 3.95$, $p < 0.040$, $\epsilon = 0.83$) indicating that hit percentages decreased with increasing magnitude of physical difference between the frequencies being employed. There was also a Stimulus-Type × Amount-of-Deviance interaction ($F_{4,56} = 3.54$, $p = 0.038$, $\epsilon = 0.55$) indicating larger deviance-related decrease in hit percentages in the Medium-Deviant and Large-Deviant conditions compared with the Small-Deviant condition. A subsequent ANOVA with factor levels of Stimulus-Type being Standard and Control (i.e., reflecting the benefits in the processing of standards relative to controls) yielded a significant main effect of Stimulus-Type ($F_{1,14} = 4.61$, $p < 0.050$). The corresponding ANOVA with Control and Deviant as levels of Stimulus-Type (i.e., reflecting costs in the processing of deviants relative to controls) yielded a marginal significant main effect of Stimulus-Type ($F_{1,14} = 3.75$, $p < 0.073$) indicating deteriorated performance for deviants compared to controls. The corresponding ANOVA with Standard and Deviant as levels of Stimulus-Type (i.e., reflecting the difference between standard and deviants) yielded a highly significant main effect of Stimulus-Type ($F_{1,14} = 15.47$, $p < 0.001$) reflecting smaller hit rates for deviants compared with standards. However, there was also a significant Stimulus-Type × Amount-of-Deviance interaction ($F_{2,28} = 6.11$, $p < 0.007$, $\epsilon = 0.94$) indicating that the difference between hit rates to the different types of stimuli was not identical for all levels of the factor Amount-of-Deviance. In subsequent ANOVAs, the differences between Deviant and Standard hit rates were compared for all pairwise Amount-of-Deviance condition combinations. They yielded significant differences between the Medium-Deviant and Small-Deviant conditions ($F_{1,14} = 12.92$, $p < 0.003$) and a marginal significant difference between the Medium-Deviant and Large-Deviant conditions ($F_{1,14} = 4.54$, $p < 0.051$).

3.3. Behavioral data: false alarm rates

Fig. 3 (right panel) shows the percentages of false alarms (i.e., button-presses to short tones) for standards, deviants, and controls, separately for the different Amount-of-Deviance conditions. False alarm percentages were higher with deviants as compared with standards (and controls) in Medium-Deviant and in Large-Deviant condition. In the Small-Deviant condition, only 5 of the 15 subjects had an increase in false alarm rate in the case of deviants relative to standards; in the Medium-Deviant condition, 9 of the 15 subjects showed an increase in false alarm rate for deviants; in the Large-Deviant condition, 11 of the subjects had an increase in false alarm rate to deviants. The omnibus-ANOVA yielded a marginal significant main effect of Stimulus-Type ($F_{2,28} = 3.57$, $p < 0.066$, $\epsilon = 0.65$). A subsequent ANOVA with factor levels of Stimulus-Type being Standard and Control (i.e., reflecting the benefits in the processing of standards relative to controls) yielded a significant main effect of Stimulus-Type ($F_{1,14} = 9.78$, $p < 0.007$). The corresponding ANOVA with Control and Deviant as levels of Stimulus-Type (i.e., reflecting costs in the processing of deviants relative to controls) yielded no main effect of Stimulus-Type ($F_{1,14} = 0.25$, $p = 0.628$). The corresponding ANOVA with Standard and Deviant as levels of Stimulus-Type (i.e., reflecting the difference between standards and deviants) yielded a significant main effect of Stimulus-Type ($F_{1,14} = 6.78$, $p < 0.021$), indicating more false alarms with deviants compared with standards. However, a marginal significant



— Deviant
-- Standard
···· Control
Small Deviant
−4μV
+3μV
700ms
Fpz
HeoG
L1
Fz
R1
L2
Cz
R2
lM
Pz
rM
Medium Deviant
−4μV
+3μV
700ms
Fpz
HeoG
L1
Fz
R1
L2
Cz
R2
lM
Pz
rM
Large Deviant
−4μV
+3μV
700ms
Fpz
HeoG
L1
Fz
R1
L2
Cz
R2
lM
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rM

Stimulus-Type × Amount-of-Deviance interaction ($F_{2,28} = 2.62$, $p < 0.102$, $\epsilon = 0.84$) indicated that the difference in false alarms between standards and deviants was not identical across the three Amount-of-Deviance conditions. Subsequent ANOVAs which were performed for the three Amount-of-Deviance conditions yielded significant main effects of Stimulus-Type in the Medium-Deviant and Large-Deviant conditions only ($F_{1,14}$-values = 5.12 and 6.13, $p < 0.027$).

3.4. ERP data: component mean amplitudes

Fig. 4 shows the ERPs elicited by the standards, deviants, and controls, separately for the different Amount-of-Deviance conditions. Fig. 5 shows the corresponding Deviant minus Standard and Deviant minus Control difference waves. Table 2 lists the mean MMN and N2b amplitudes elicited at Fz and lM. The corresponding t-tests yielded significant results except the Fz MMN from the Large-Deviant condition measured from the Deviant minus Control difference waves and the left mastoid N2bs obtained in the Small-Deviant condition. Distinct MMNs were elicited, which revealed polarity reversals at the mastoids. This was revealed by the traditional subtraction method and by the modified subtraction method. The MMNs were followed by N2b deflections which did not invert polarity at the mastoids. Finally, there were distinct P3 deflections which were of comparable amplitudes at Fz, Cz, and Pz. The corresponding t-tests yielded significant results in each Amount-of-Deviance condition (Table 3). It should be noted that deviants elicited an additional, fronto-centrally distributed negativity in the 400–700 ms range (Fig. 4). This unexpected effect will not be discussed in this paper.

The ANOVAs comparing the MMNs across the Small-, Medium-, and Large-Deviant conditions yielded a marginally significant Amount-of-Deviance main effect with the traditional subtraction method ($F_{2,28} = 2.54$, $p < 0.109$, $\epsilon = 0.82$) reflecting smallest MMN amplitude in the Small-Deviant condition. However, with the modified subtraction method, the significant Amount-of-Deviance main effect ($F_{2,28} = 4.80$, $p < 0.021$, $\epsilon = 0.88$) was due to largest MMN amplitude in the Small-Deviant condition. The ANOVA performed with the N2bs computed with the modified subtraction method yielded a marginally significant Amount-of-Deviance main effect ($F_{2,28} = 2.77$, $p < 0.091$, $\epsilon = 0.84$). This effect was mainly due to largest N2b in the Small-Deviant condition. As can be seen in Table 3, the P3 amplitudes were increasing with increasing difference between standard and deviants. This observation was confirmed by ANOVAs performed with the P3 computed with the traditional ($F_{2,28} = 4.53$, $p < 0.020$, $\epsilon = 0.99$) and the modified ($F_{2,28} = 4.24$, $p < 0.027$, $\epsilon = 0.94$) subtraction method.

3.5. ERP data: component latencies

For the traditional subtraction method, the means of the individual MMN peak latencies were 169, 142, and 141 ms for the Small-, Medium-, and Large-Deviant conditions ($F_{2,28} = 10.89$, $p < 0.001$, $\epsilon = 0.76$). Subsequent pairwise t-tests revealed prolonged MMN latencies in the case of the Small-Deviant condition compared with the Medium- and Long-Deviant conditions ($t_{14} = 4.24$ and 3.33, $p < 0.001$ and.005, respectively). For the modified subtraction method, mean individual MMN peak latencies were 199, 145, and 113 ms ($F_{2,28} = 44.11$, $p < 0.001$, $\epsilon = 0.62$). The Amount-of-Deviance main effect was due to longest MMN latencies in the Small-Deviant condition (Small vs. Medium: $t_{14} = 9.52$, $p < 0.001$) and to shortest MMN latencies in the Large-Deviant condition (Large vs. Small: $t_{14} = 9.88$, $p < 0.001$; Large vs. Medium: $t_{14} = 2.58$, $p < 0.022$).

Also the N2b latencies decreased with increasing magnitude of physical difference between deviant and standard. For the traditional subtraction method, the means of the individual N2b peak latencies were 251, 221, and 201 ms for the Small-, Medium-, and Large-Deviant conditions ($F_{2,28} = 12.32$, $p < 0.001$, $\epsilon = 0.69$). The corresponding values for the modified subtraction method were 260, 224, and 209 ms ($F_{2,28} = 21.13$, $p < 0.001$, $\epsilon = 0.73$). Subsequent pairwise t-test yielded prolonged latencies for the Small-Deviant condition (Small vs. Medium: $t_{14} = 2.24$ and 3.58 for the traditional and the modified subtraction method, $p < 0.042$ and.003) and shortest N2b latencies for the Large-Deviant condition (Large vs. Small: $t_{14} = 5.60$ and 6.44 for the traditional and the modified subtraction method, $p < 0.001$ and.001; Large vs. Medium: $t_{14} = 2.74$ and 2.70 for the traditional and the modified subtraction method, $p < 0.016$ and.017).

The means of the individual P3 peak latencies were 345, 337, and 325 ms for the Small-, Medium-, and Large-Deviant conditions in the case of the traditional subtraction method. With the modified subtraction method, P3 peak latencies were 343, 338, and 322 ms for the three Amount-of-Deviance conditions. The corresponding ANOVAs failed to reach statistical significance.

4. Main experiment: discussion

4.1. Behavioral distraction effects elicited by small distractors

The present paradigm yielded reliable distraction on an individual level even with deviants revealing a frequency

Fig. 4. Grand-average ERPs elicited by for standard (broken lines), control (dotted lines), and deviant (continuous lines) stimuli, separately for the Small, Medium, and Large Amount-of-Deviance conditions. The time and amplitude scales are shown in the upper left corner of each box (main experiment).

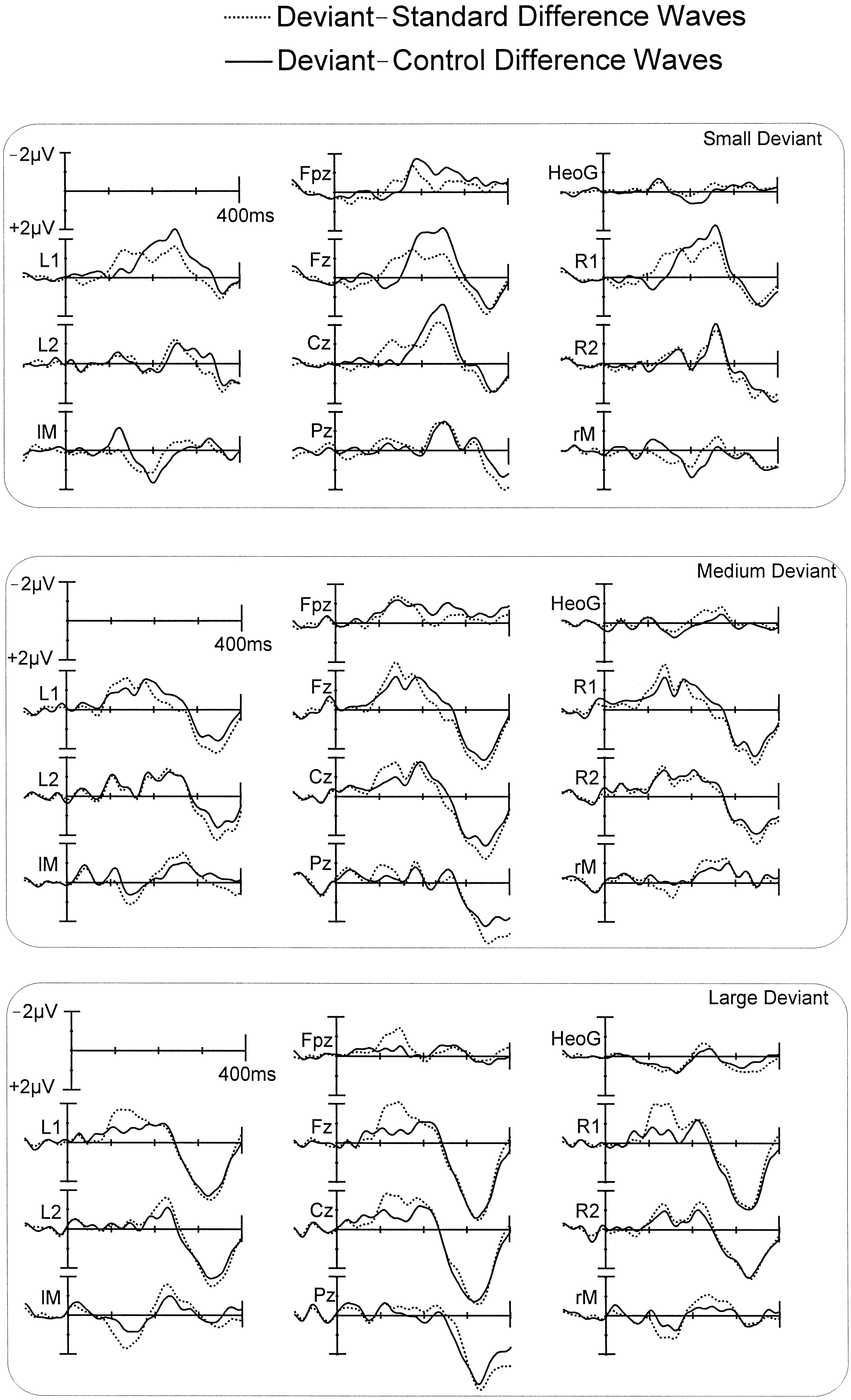
Deviant–Standard Difference Waves
Deviant–Control Difference Waves
Small Deviant
Medium Deviant
Large Deviant
−2μV
+2μV
400ms
Fpz
HeoG
L1
Fz
R1
L2
Cz
R2
lM
Pz
rM

Table 2
MMN and N2b mean amplitudes for Fz and left mastoid (lM) electrode locations, separately for the small, medium, and large amount-of-deviance conditions

		MMN			N2b		
		Deviant			Deviant		
		Small	Medium	Large	Small	Medium	Large
Fz	Dev-Stand	−1.29*** (175)	−2.00*** (135)	−1.95*** (140)	−0.97* (255)	−1.54** (180)	−0.92* (210)
	Dev-Contr	−2.28*** (210)	−1.36*** (140)	−0.60 (110)	−2.20*** (255)	−1.43*** (180)	−1.03* (210)
lM	Dev-Stand	+1.00* (195)	+.80** (140)	+1.47** (130)	−0.42 (280)	−1.29*** (265)	−1.24** (225)
	Dev-Contr	+1.29** (200)	+0.35 (145)	+0.78* (145)	−0.40 (330)	−0.93** (270)	−0.75* (235)

One-tailed *t*-test: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
Values in parentheses represent the peak latency (ms) of the respective component in the grand-average Deviant minus Standard and Deviant minus Control responses. Individual MMN and N2b amplitudes were measured in the 50-ms interval around these latencies.

deviation of about 7% (Fig. 6). The behavioral distraction effects obtained with tiny deviants can be explained within the framework of a particular change-detection mechanism. As shortly mentioned in Section 1, there is evidence for three types of deviant detection mechanisms: (1) Large changes or novels may be detected on the basis of differential refractoriness of afferent elements specifically responding to the features of the standard, and afferent elements specifically responding to the features of the deviant [41]. (2) Tiny changes may be detected on the basis of an automatically operating system which (a) extracts actual stimulus information, (b) encodes invariances in repetitive input into shortlived representations of sensory memory, and (c) compares the actually generated representations with the representation of the invariances. It has been demonstrated elsewhere that MMN elicited by tiny deviants cannot be explained by the differential refractoriness hypothesis and may, therefore, be regarded as an indicator of this memory-related change-detection system [42,58]. (3) Meaningful events may be detected on the basis of match processes comparing each input with a limited set of representations stored in long-term memory. The output of any of these change-detection mechanisms may result in the elicitation of an attention switch causing deteriorated performance in the primary task. With large deviants and novels it is unclear whether only one or several of these mechanisms contribute to the distraction effect. However, in the present paradigm employing tiny changes, the distraction effect can only be explained by the memory-related change-detection mechanism. Thus, the present paradigm is suited to yield distraction effects that can most likely be interpreted in terms of a particular mechanism. This may help to further illuminate the processes underlying distraction.

4.2. How to explain the occurrence of behavioral distraction with small distractors

On the average, the RT to targets with a small frequency deviation were prolonged by about 50 ms relative to targets being of standard frequency. This effect exceeds the RT prolongation obtained in previous distraction experiments by a factor of five [55] and seven [13]. However, the frequency difference between standard and deviant employed in the present study was almost identical to these studies, and also the timing of the onset of task-relevant aspects of stimulation (target) and the onset of the task-irrelevant, distracting aspect of the stimulation (frequency deviation) was comparable. That is, the difference in the size of the distraction effect cannot be explained by the amount of the physical difference between deviant and standard or by a difference in the timing of the presentation of the deviant. Instead, the pattern of results suggest that the channel-separation is important for the size of the behavioral distraction effect [9]. Channel-separation was maximal in the study by Escera et al. [13], in which the distracting deviant stimuli and the target stimuli occurred in separate modalities. It was intermediate in the study by Schröger [55] in which targets and distractors were both auditory but presented to different ears. Channel-separation was minimal in the present study, in which deviant and target dimension were embedded in the same

Fig. 5. Traditional difference waves, which were computed by subtracting the ERPs elicited by the standard from those elicited by the deviant, and modified difference waves, which were computed by subtracting the ERPs elicited by the control from those elicited by the deviant. The time and amplitude scales are shown in the upper left corner of each box (main experiment).

Table 3
P3 mean amplitudes for Fz electrode location, separately for the small, medium, and large amount-of-deviance conditions

		P3		
		Deviant		
		Small	Medium	Large
Fz	Dev-Stand	+1.57* (350)	+2.72** (345)	+3.60*** (330)
	Dev-Contr	+1.31* (365)	+2.31** (345)	+3.55*** (325)

One-tailed t-test: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
Values in parentheses represent the peak latency (ms) of the P3 in the respective grand-average Deviant minus Standard and Deviant minus Control responses. Individual amplitudes were measured in the 50-ms interval around these latencies.

perceptual object but located in different dimensions of this object. Similar observations have been made in visual distraction [5,11,30]. Moreover, this finding also supports the notion that our auditory system creates meaningful units of the acoustic input by integrating information that belongs together and separating it from information belonging to different objects [7]. Effects of the way our auditory system organizes the acoustic input on behavioral performance and ERPs have been demonstrated in previous studies (e.g., Refs. [2,62,65]).

A similar argument can be made for the elicitation of N2b and P3a components presumably indicating the conscious registration of the deviance. In ignore condition, task-irrelevant frequency deviations of about 7% elicit a MMN, but they usually do not evoke N2b and P3a. The MMN obtained in the present paradigm is quite similar to the MMN obtained in different types of paradigms trying to prevent that the subjects attended to the standard and deviant sounds, such as reading [43], dichotic listening [44], and crossmodal attention [3]. This suggests that automatic deviance-detection (reflected in MMN) is not affected by a reduction in channel-separation. However, with the present setting, it seems to be difficult for the subject to get rid of task-irrelevant stimulus information. That is, the information about the presence of a deviant event (provided by the automatic deviant-detection system indexed by the elicitation of MMN) evokes subsequent processes resulting in an orienting towards the deviance (indicated by the elicitation of N2b and P3a, as well as by the occurrence of behavioral distraction effects) when task-irrelevant, distracting aspects of the stimulation and task-relevant aspects of stimulation belong to the same sound.

4.3. Influence of the amount of deviation

With respect to the influence of the amount of deviation on the latencies of the deviance-related ERP effects (MMN, N2b, P3a), the findings are consistent with previous research. That is, the observed decrease in MMN-latency, in N2b-latency, and (only numerically) in P3a-latency with increasing deviant-standard difference has to be expected according to results reported by Novak et al. [46,47]. With

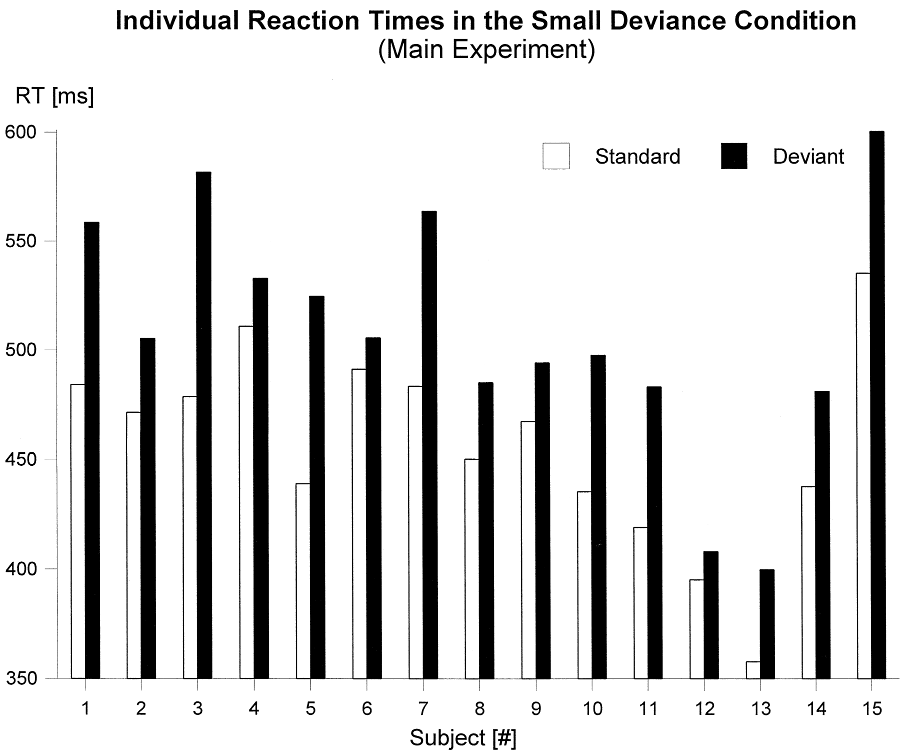

Fig. 6. Individual reaction times to target stimuli (i.e., long duration tones), separately for standard and deviant stimuli obtained the Small Amount-of-Deviance condition (main experiment).

respect to the influence of the amount of deviation on the size of the behavioral distraction effect, the findings are not homogeneous. On the one hand, RT prolongation obtained with deviants did not (significantly) increase as a function of the physical difference between deviant and standard. On the other hand, false alarm rates were affected by the amount of deviance. That is, with medium and large deviants more incorrect responses were made than with small deviants.

With the traditional Deviant minus Standard comparison, MMN and P3a amplitudes increased with increasing amount of deviance. This has to be expected on the basis of previous research [41]. The unexpected absence of an increase of N2b with increasing difference between deviant and standard can be explained by the partial overlap between the P3a and the N2b in the present paradigm. That is, the P3a is already developing before the N2b is terminated, resulting in an artificial decrease of the N2b. It is somewhat puzzling that the MMN delineated by the modified Deviant minus Control comparison did not increase as a function of increasing amount of deviation. A possible explanation could be that the 'MMN' delineated by the traditional Deviant vs. Standard comparison consists of N1-refractoriness effects and of a true MMN [42,53]. Then, the findings of the control condition (in which the N1-refractoriness effect was controlled for) would suggest that the assumed relationship between MMN-amplitude and amount of deviance [63] does mainly hold for the memory-unrelated part of the deviance-related negativity but not (or only within a limited range of deviations) for its memory-related part. That is, if the deviance becomes too large (as in the Large Deviant condition of the present experiment) MMN is possibly not increased anymore (or may even be reduced in amplitude), since another change-detection mechanism comes into play, namely, the 'new-afferent-elements' mechanism (cf. Section 1). However, this represents a post-hoc explanation of an unexpected result and needs further research.

4.4. Decomposition of behavioral distraction effects in costs and benefits

The cost–benefit analysis of RTs (performed in analogy to the method provided by Posner [50]) revealed that the distraction consisted both in a modulation (i.e., prolongation) in the processing of targets with deviant frequency (costs) and in a modulation (i.e., acceleration) in the processing of targets with standard frequency (benefits). The existence of costs is a prerequisite for connecting behavioral distraction effects with deviance-related ERP effects (which are known to reflect a modulation in the processing of deviant stimuli). In this respect, the present demonstration of costs in auditory distraction creates a necessary contribution to research trying to link behavioral and electrophysiological distraction measures. In addition, the occurrence of costs is evidence against the hypothesis that the behavioral distraction completely results from a stimulus probability effect [31,39] since deviant and control stimuli had identical probabilities. Only the benefits revealed by the Standard vs. Control comparison may possibly reflect stimulus probability effects.

The existence of acceleration of RTs with targets of standard frequency relative to targets when frequency varies from trial to trial suggests that we may benefit from constancy in the frequency dimension for the evaluation of the duration dimension. This may be interpreted as indicating that the duration and the frequency of a sound are not processed completely independent of each other. The finding that task-irrelevant frequency deviations impair duration discrimination suggests that these stimulus dimensions form integrable rather than separable dimensions [18,28,38]. One criterion for integrable dimension is the occurrence of interference in a classification task when one of the dimensions is used as an irrelevant dimension. However, this cannot necessarily be expected on the basis of findings demonstrating that the preattentive processing of these dimensions happens in spatially distinct [19] and functionally separate [32,67] regions of the brain.

According to an alternative interpretation, the so-called benefits may be regarded as costs in the processing of targets in control blocks. If one considers that frequency changes from trial to trial in control blocks, it seems possible that our attentional system is permanently tempted to scan the task-irrelevant frequency dimension and, as a consequence, has less processing capacity available for performing the duration discrimination. This re-interpretation of benefits into costs is consistent with findings from Jones et al. [25,27] according to which discretely presented, irrelevant tones changing over time may impair performance in a visual memory task. It is further supported by the present finding that the N1 elicited by control stimuli is consistently enhanced relative to the N1 elicited by standard stimuli (Fig. 4), suggesting that the attention switching system reflected in the N1-refractoriness-effects is stronger activated by control stimuli in control blocks than by standard stimuli in oddball blocks.

If the difference yielded by the comparison of Control-RTs vs. Standard-RTs merely reflects costs in the processing of control stimuli (instead of benefits in the processing of standard stimuli), then the comparison of Deviant-RTs vs. Control-RTs even underestimates the true costs elicited by deviant stimuli. That is, the Deviant-RTs minus Control-RTs of our decomposition of the distraction effects into costs and benefits represent the minimal costs for deviants and the maximal benefits for standards. However, the true RT costs elicited by deviants may be as large as the Deviant-RTs minus Standard-RTs.

5. Control experiments

Since a new distraction paradigm was used in the main experiment, two control experiments were performed in order to replicate the behavioral distraction effects and the electrophysiological deviance-related effects. In these control experiments, we introduced several variations to determine the robustness of these effects obtained with tiny deviations. The most important difference to the main experiment consists in the fact that each stimulus was a target requiring a behavioral response, whereas in the main experiment, only 50% of the stimuli required an overt response and the remaining 50% required the withholding of a response.

5.1. Control experiments: materials and methods

5.1.1. Control experiment 1

5.1.1.1. Subjects. Fourteen paid healthy subjects (ages 22–35 years, mean 28.3 years; 8 male) reporting normal hearing participated in the experiment. Subjects were seated in a comfortable chair in an electrically shielded and acoustically attenuated cabin during the experiment.

5.1.1.2. Procedure. Everything was kept identical to the oddball condition of the main experiment except the following changes. Subjects had to respond to each stimulus; in one half of the experimental blocks, long stimuli required a response with the left index-finger, and short stimuli required a response with the right index-finger; in the other half, stimulus–response mapping was reversed. In three conditions, the duration of short and long tones was 30 vs. 180 ms, 150 vs. 300 ms, and 200 vs. 400 ms. There were 12 experimental blocks containing 320 trials for each condition. The standard frequency was 1000 Hz, the deviant frequency was either 900 or 1100 Hz ($p = 0.05$ each).

5.1.1.3. Data analysis. RTs, hit rates, and false alarms were computed analogous to the main experiment, separately for the three duration conditions. ANOVAs including Stimulus-Type (levels: Standard, Deviant) and Duration (levels: 30/180, 150/300, 200/400) as within-subjects factors were computed.

5.1.2. Control experiment 2

5.1.2.1. Subjects. Three paid healthy subjects (ages 27–32 years, mean 30.0 years; 3 male) reporting normal hearing participated in the experiment. Subjects were seated in a comfortable chair in an electrically shielded and acoustically attenuated cabin during the experiment.

5.1.2.2. Procedure. Everything was kept identical to the oddball condition of the main experiment except the following changes. Subjects had to respond to each stimulus; in one half of the experimental blocks, long stimuli required a response with the left index-finger, and short stimuli required a response with the right index-finger; in the other half, stimulus–response mapping was reversed. The duration of short and long tones was 200 and 400 ms, respectively. Instead of the ISI, the stimulus-onset asynchrony (SOA) was held constant at 1300 ms. There were eight experimental blocks, each containing 80 trials. The EEG was measured with Ag–Ag/Cl electrodes from 30 scalp locations including Fp1, F3, Fz, F4, Cz, Pz, and left and right mastoid. The reference electrode was positioned at the nose. The horizontal EOG and the vertical EOG were monitored with electrodes placed at the outer canthi of the left and right eye, and above and below the right eye, respectively. The EEG and EOG were digitized by NeuroScan data-acquisition unit at a rate of 200 Hz and with a filter bandpass of 0.1 to 40 Hz. Epochs were 800 ms in duration (including a 100 ms prestimulus baseline). Epochs with EEG or EOG exceeding ± 60 μV were rejected from further analysis.

5.1.2.3. Data analysis. RTs, hit rates, and false alarms were computed analogous to the main experiment. Difference waves were formed by subtracting Standard-ERPs from Deviant-ERPs.

5.2. Control experiments: results and discussion

In control experiment 1, each subject revealed prolonged RTs to targets being of deviant frequency relative to targets being of standard frequency (Fig. 7). This finding was reflected in the ANOVA yielding a main effect of the factor Stimulus-Type ($F_{1, 13} = 43.41$, $p < 0.001$; the main effect Duration and the interaction effect Stimulus-Type $\times$ Duration were not significant). Trials with targets being of deviant frequency revealed lower hit rates (89.5% vs. 93.7; $F_{1,13} = 22.58$, $p < 0.001$; the main effect Duration and the interaction effect Stimulus-Type $*$ Duration were not significant) and increased false alarms (7.8% vs. 3.9%; $F_{1, 13} = 17.66$, $p < 0.001$; the main effect Duration and the interaction effect Stimulus-Type $*$ Duration were not significant). In control experiment 2, each subject revealed behavioral distraction consisting in slower RTs in deviant trials (348 ms vs. 316 ms). The deviance-related ERP effects consisted of MMN and P3a (Fig. 8).

In both control experiments, the behavioral distraction effects obtained in the main experiment could be replicated successfully. Although target probability, stimulus response mapping, and duration of short and long stimuli were different from the main experiment, the amount of the distraction effect was virtually identical. Within the set of durations utilized in the control experiments, the distraction effect did not vary as a function of duration. Subjects in the main experiment performed a Go/Nogo task, that is, anticipatory motor response strategies might have been developed by some subjects, in which a response was readied on all trials, and then inhibited when the short

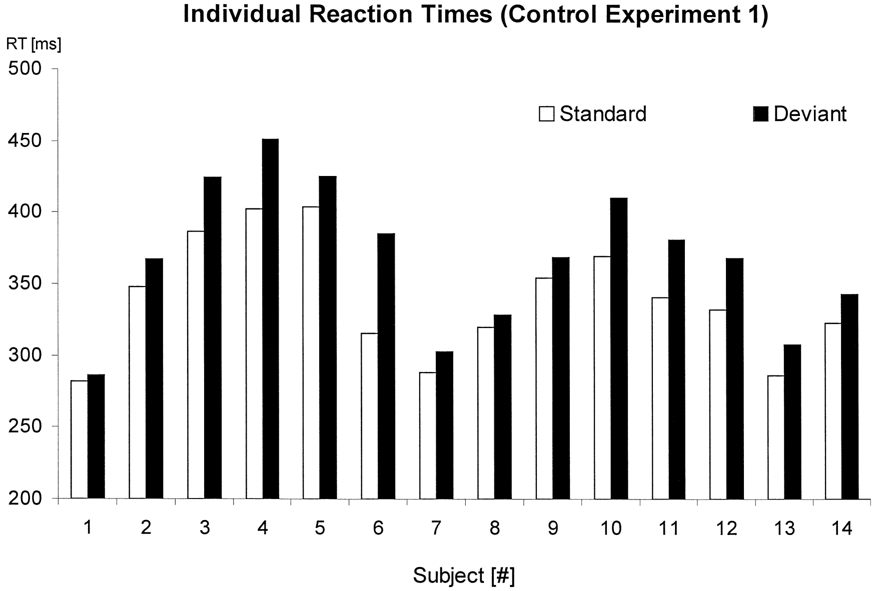

Fig. 7. Individual reaction times to target stimuli, separately for targets being of standard frequency and of deviant frequency (control experiment 1).

duration stimulus (Nogo) occurred. Although particular Go/Nogo effects (e.g., Refs. [12,16,24,35,49,54]) cannot be excluded, they would probably affect standard and deviant trials to the same degree, and would therefore not modulate the distraction effects. Nevertheless, since all trials required a behavioral response in the control experiments, the distraction effects could not have been modulated by Go/Nogo effects there. Furthermore, the usage of a two-alternative-forced-choice version of the distraction paradigm has the advantage, that less trials are needed to collect the same amount of behavioral responses than with the Go/Nogo version of the distraction paradigm. This could be helpful in studying distraction with clinical populations. It should also be noted, the deviance-related ERP effects between the main experiment and control experiment 2 are highly similar; that is, distinct MMN and P3a effects were obtained with the present distraction paradigm.

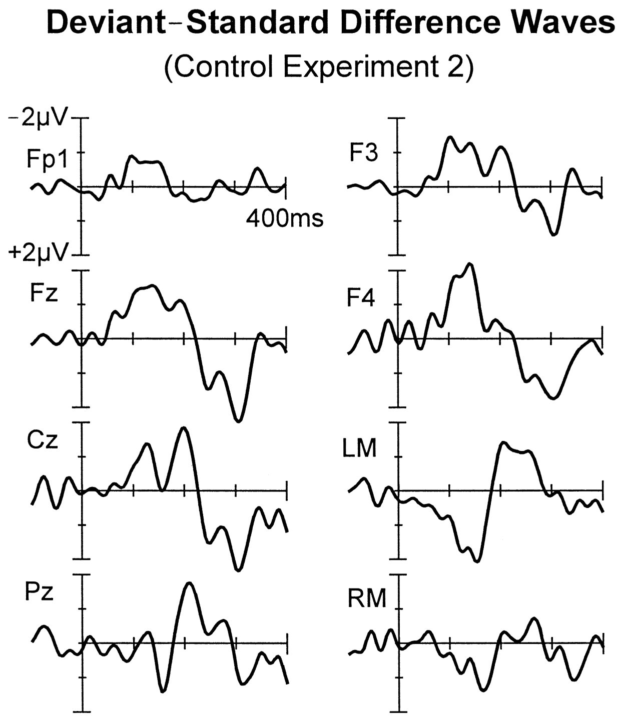

Fig. 8. Difference waves computed by subtracting the ERPs to targets being of standard frequency from ERPs to targets being of deviant frequency (control experiment 2).

6. Conclusions

There is evidence that many areas of the brain (e.g. supratemporal, prefrontal, and hippocampal regions) are active in the processing of task-irrelevant deviant or novel sounds (e.g., [21,22,29,37]). It seems likely that deviance-related processing taking place in these areas is involved in the phenomenon of auditory distraction. Combining measures of deviance-related brain activity (such as particular ERP effects) with behavioral measures may help to further illuminate the neural processes underlying the presence or absence of distraction in particular circumstances. Before linking behavioral and electrophysiological measures of distraction, it must be assessed that they reflect the same phenomenon. The present study delivered some evidence for this hypothesis. Moreover, the behavioral distraction effects often cannot be interpreted unequivocally with regard to the underlying attention switching mechanism. The present study delivered evidence that rather small deviations in our acoustic environment may cause reliable impairment in behavioral performance. In this case, it is likely that a particular memory-related change-detection mechanism (indicated by MMN) is involved. If a discrepancy is detected by this automatically operating change-detection mechanism, an attention switch may be triggered, resulting in an orienting towards the perturbating event (indicated by P3a). As a consequence, less processing resources are devoted to performing the task which, in turn, results in a decrease in behavioral performance. However, in order to trigger an attention switch, some variable threshold has to be exceeded by the mismatch signal. By embedding task-irrelevant and task-relevant aspects of stimulation into the same perceptual object, the probability for exceeding this threshold is increased. This is indicated by the finding that rather small deviances impaired behavioral performance in every subject. Due to the reliable baseline effect, not only an increase in distractability, but also a decrease in distractability can be assessed with the present paradigm. [2] Thus, the present paradigm may possibly be utilized for clinical studies.

Acknowledgements

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References

[1] C. Alain, D.L. Woods, Distractor clustering enhances detection speed and accuracy during selective listening, Percept. Psychophys. 54 (1993) 509–514.
[2] C. Alain, D.L. Woods, Signal clustering modulates auditory cortical activity in humans, Percept. Psychophys. 56 (1994) 501–516.
[3] K. Alho, D.L. Woods, A. Algazi, Processing of auditory stimuli during auditory and visual attention as revealed by event-related potentials, Psychophysiology 31 (1994) 469–479.
[4] K. Alho, D.L. Woods, A. Algazi, R. Näätänen, Intermodal selective attention: II. Effects of attentional load on processing of auditory and visual stimuli in central space, Electroencephalogr. Clin. Neurophysiol. 82 (1992) 356–368.
[5] G.C. Baylis, J. Driver, Visual parsing and response competition: the effect of grouping factors, Percept. Psychophys. 51 (1992) 145–162.
[6] A.S. Bernstein, The orienting response and direction of stimulus change, Psychonomic Sci. 12 (1968) 127–128.
[7] A.S. Bregman, Auditory Scene Analysis, The MIT Press, Cambridge, MA, 1990.
[8] A.S. Bregman, A.I. Rudnicky, Auditory segregation: stream or streams?, J. Exp. Psychol.: Hum. Percept. Perform. 1 (1975) 263–267.

[2] Indeed, such a decrease has been observed in a recent study by Jääskeläinen et al. utilizing the present paradigm [23]. Relative to a placebo condition, small doses of ethanol were found to reduce the behavioral distraction effect.

[9] D.E. Broadbent, Decision and Stress. Academic Press, London, 1971.
[10] M.E. Dawson, D.L. Filion, A.M. Schell, Is elicitation of the autonomic orienting response associated with allocation of processing resources?, Psychophysiology 26 (1989) 560–572.
[11] J. Driver, G.C. Baylis, Target–distractor separation and feature integration in visual attention to letters, Acta Psychol. 76 (1991) 101–119.
[12] M. Eimer, Effects of attention and stimulus probability on ERPs in a Go/Nogo task, Biol. Psychol. 35 (1993) 123–138.
[13] C. Escera, K. Alho, I. Winkler, R. Näätänen, Neural mechanisms of involuntary attention to acoustic novelty and change, J. Cogn. Neurosci, in press.
[14] D.L. Filion, M.E. Dawson, A.M. Schell, E.A. Hazlett, The relationship between skin conductance orienting and the allocation of processing resources, Psychophysiology 28 (1991) 410–424.
[15] P.G. Fitzgerald, T.W. Picton, Event-related potentials recorded during the discrimination of improbable stimuli, Biol. Psychol. 17 (1983) 241–276.
[16] M. Falkenstein, N.A. Koshlykova, V.N. Kiroj, J. Hoormann, J. Hohnsbein, Late ERP components in visual and auditory Go/Nogo tasks, Electroencephalogr. Clin. Neurophysiol. 96 (1995) 36–43.
[17] M. Fredrikson, T. Berggren, G. Wanko, B. von Scheele, Habituation and dishabituation of the orienting reaction to between and within trial changes in pitch and loudness, Psychophysiology 21 (1984) 219–227.
[18] W.R. Garner, The Processing of Information and Structure, Wiley, New York, 1974.
[19] M.H. Giard, J. Lavikainen, K. Reinikainen, F. Perrin, O. Bertrand, J. Pernier, R. Näätänen, Separate representations of stimulus frequency, intensity, and duration in auditory sensory memory, J. Cogn. Neurosci. 7 (1995) 133–143.
[20] C. Grillon, E. Courchesne, R. Ameli, R. Elmasian, D. Braff, Effects of rare non-target stimuli on brain electrophysiological activity and performance, Int. J. Psychophysiol. 9 (1990) 257–267.
[21] E. Halgren, P. Baudena, J.M. Clarke, G. Heit, C. Liegeois, P. Chauvel, A. Musolino, Intracerebral potentials to rare target and distractor auditory and visual stimuli: I. Superior temporal plane and parietal lobe, Electroencephalogr. Clin. Neurophysiol. 94 (1995) 191–220.
[22] R. Hari, M. Hämäläinen, R. Ilmoniemi, E. Kaukoranta, K. Reinikainen, J. Salminen, K. Alho, R. Näätänen, M. Sams, Responses of the primary auditory cortex to pitch changes. Neuromagnetic recordings in man, Neurosci. Lett. 50 (1984) 127–132.
[23] I.P. Jääskeläinen, E. Schröger, R. Näätänen, Effects of ethanol on auditory distraction: an ERP and behavioral study, Psychopharmacology, in revision.
[24] E. Jodo, Y. Kayama, Relation of a negative ERP component to response inhibition in a Go/No-go task, Electroencephalogr. Clin. Neurophysiol. 82 (1992) 477–482.
[25] D.M. Jones, W.J. Macken, Irrelevant tones produce an irrelevant speech effect: Implications for phonological coding in working memory, J. Exp. Psychol.: LMC 19 (1993) 369–381.
[26] M.R. Jones, G. Kidd, R. Wetzel, Evidence for rhythmic attention, J. Exp. Psychol. Hum. Percept. Perform. 7 (1981) 1059–1073.
[27] D.M. Jones, W.J. Macken, A.C. Murray, Disruption of visual short-term memory by changing-state auditory stimuli: the role of segmentation, Mem. Cognit. 21 (1993) 318–328.
[28] D.G. Kemler Nelson, Processing integral dimensions: the whole view, J. Exp. Psychol.: Hum. Perc. Perform. 19 (1993) 1105–1113.
[29] R.T. Knight, Contribution of human hippocampal region to novelty detection, Nature 383 (1996) 256–259.
[30] A. Kramer, A. Jacobson, Perceptual organization and focused attention: the role of objects and proximity in visual processing, Percept. Psychophys. 50 (1991) 267–284.
[31] E. Krinchik, Probability effects in choice reaction time tasks, Percept. Psychophys. 15 (1974) 131–144.

[32] S. Levänen, R. Hari, L. McEvoy, M. Sams, Responses of the human auditory cortex to changes in one vs. two stimulus features, Exp. Brain Res. 97 (1993) 177–183.
[33] N. Loveless, S. Levänen, V. Jousmäki, M. Sams, R. Hari, Temporal integration in auditory sensory memory: neuromagnetic evidence, Electroencephalogr. Clin. Neurophysiol. 100 (1996) 220–228.
[34] Z.L. Lü, S.J. Williamson, L. Kaufman, Behavioral lifetime of human auditory sensory memory predicted by physiological measures, Science 258 (1992) 1668–1670.
[35] S. Mäntysalo, N2 and P3 of the ERP to Go and Nogo stimuli: A stimulus–response association and dissociation, in: R. Johnson Jr., J.W. Rohrbaugh, R. Parasuraman (Eds.), Current Trends in Event-Related Potential Research (EEG Suppl. 40) Elsevier, Amsterdam, 1987, pp. 227–324.
[36] A. Mecklinger, B. Opitz, A.D. Friederici, Semantic aspects of novelty detection in humans, Neurosci. Lett. 235 (1997) 65–68.
[37] A. Mecklinger, P. Ullsperger, The P300 to novel and target events: a spatiotemporal dipole model analysis, NeuroReport 7 (1995) 241–245.
[38] R.D. Melara, L.E. Marks, Perceptual primacy of dimensions: support for a model of dimensional interaction, J. Exp. Psychol.: Hum. Percept. Perform. 16 (1990) 398–414.
[39] J.O. Miller, R.G. Pachella, Locus of the stimulus probability effect, J. Exp. Psychol. 101 (1973) 227–231.
[40] R. Näätänen, The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function, Behav. Brain Sci. 13 (1990) 201–288.
[41] R. Näätänen, Attention and Brain Function, Erlbaum, Hillsdale, NJ, 1992.
[42] R. Näätänen, K. Alho, Higher-order processes in auditory change detection, Trends Cogn. Sci. 2 (1997) 44–45.
[43] R. Näätänen, A.W.K. Gaillard, S. Mäntysalo, Early selective attention effect on evoked potential reinterpreted, Acta Psychol. 42 (1978) 313–329.
[44] R. Näätänen, P. Paavilainen, H. Tiitinen, D. Jiang, K. Alho, Attention and mismatch negativity, Psychophysiology 30 (1993) 436–450.
[45] M. Niepel, U. Rudolph, A. Shutzwohl, W.U. Meyer, Temporal characteristics of the surprise reaction induced by schema-discrepant visual and auditory events, Cogn. Emotion 8 (1994) 433–452.
[46] G. Novak, W. Ritter, H.G. Vaughan Jr., Mismatch detection and the latency of temporal judgements, Psychophysiology 29 (1992) 398–411.
[47] G. Novak, W. Ritter, H.G. Vaughan Jr., The chronometry of attention-modulated processing and automatic mismatch detection, Psychophysiology 29 (1992) 412–430.
[48] A. Öhman, The orienting response, attention, and learning: an information-processing perspective, in: H.D. Kimmel, E.H. van Olst, J.F. Orlebeke (Eds.), The Orienting Response in Humans, Erlbaum, Hillsdale, NJ, 1979, pp. 443–471.
[49] A. Pfefferbaum, J.M. Ford, B.J. Weller, B.S. Kopell, ERPs to response production and inhibition, Electroencephalogr. Clin. Neurophysiol. 59 (1985) 85–103.
[50] M.I. Posner, Chronometric Explorations of Mind, Erlbaum, New York, 1978.
[51] P. Salamé, H. Otzenberger, Sleepinertia, noise and cognitive performance, in: A. Schick, M. Klatte (Eds.), Contributions to Psychological Acoustics, Results of the Sixth Oldenburg Symposium on Psychological Acoustics. Bibliotheks- und Informationssystem der Universität Oldenburg, Oldenburg, 1993, pp. 643–656.
[52] M. Sams, P. Paavilainen, K. Alho, R. Näätänen, Auditory frequency discrimination and event-related potentials, Electroencephalogr. Clin. Neurophysiol. 62 (1985) 437–448.
[53] M. Scherg, J. Vajsar, T.W. Picton, A source analysis of the late human auditory evoked potentials, J. Cogn. Neurosci. 1 (1989) 336–355.
[54] E. Schröger, Event-related potentials to auditory stimuli succeeding transient shifts of spatial attention in a Go/Nogo task, Biol. Psychol. 36 (1993) 183–207.
[55] E. Schröger, A neural mechanism for involuntary attention shifts to changes in auditory stimulation, J. Cogn. Neurosci. 8 (1996) 527–539.
[56] E. Schröger, Higher-order processes in auditory-change detection: response from Schröger, Trends Cogn. Sci. 2 (1997) 45–46.
[57] E. Schröger, On the detection of auditory deviants: a pre-attentive activation model, Psychophysiology 34 (1997) 245–257.
[58] E. Schröger, Ch. Wolff, Mismatch response of the human brain to changes in sound location, NeuroReport 7 (1996) 3005–3008.
[59] E.N. Sokolov, Perception and the Conditioned Reflex, Pergamon, Oxford.
[60] E.N. Sokolov, The neuronal mechanisms of the orienting reflex, in: E.N. Sokolov, O.S. Vinogradova (Eds.), Neuronal Mechanisms of the Orienting Reflex, Wiley, Hillsdale, NJ, 1975, pp. 217–338.
[61] N.K. Squires, K.C. Squires, S.A. Hillyard, Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man, Electroencephalogr. Clin. Neurophysiol. 38 (1975) 387–401.
[62] E. Sussman, W. Ritter, H.G. Vaughan Jr., An investigation of the auditory streaming effect using event-related brain potentials. Psychophysiology (in press).
[63] H. Tiitinen, P. May, K. Reinikainen dNää, R. Näätänen, Attentive novelty detection in humans is governed by pre-attentive sensory memory, Nature 372 (1994) 90–92.
[64] M.A. Uusitalo, S.J. Williamson, M.T. Seppa, Dynamical organisation of the human visual system revealed by lifetimes of activation traces, Neurosci. Lett. 213 (1996) 149–152.
[65] I. Winkler, Necessary and sufficient conditions for the elicitation of the mismatch negativity, in: C. Ogura, Y. Koga, M. Shimokochi (Eds.), Recent Advances in Event-Related Brain Potentials Research, Proceedings of the XIth International Conference on Event-Related Brain Potentials (EPIC), Okinawa, Japan, June 25–30. Elsevier, Amsterdam, 1996, pp. 36–43.
[66] I. Winkler, E. Schröger, Storing temporal features of complex sound patterns in auditory sensory memory, NeuroReport 6 (1995) 690–694.
[67] Ch. Wolff, E. Schröger, MMN elicited by one-, two-, and three-dimensional deviants, J. Psychophysiol. 9 (1995) 374.
[68] D.L. Woods, The physiological basis of selective attention: Implications of event-related potential studies, in: J.W. Rohrbaugh, R. Parasuraman, R. Johnson Jr. (Eds.), Event-related Potentials: Basic Issues and Applications. Oxford Univ. Press, Oxford, 1990, pp. 178–209.
[69] D.L. Woods, K. Alho, A. Algazi, Intermodal selective attention: I. Effects on event-related potentials to lateralized auditory and visual stimuli, Electroencephalagr. Clin. Neurophysiol. 82 (1992) 341–355.
[70] D.L. Woods, R.T. Knight, D. Scabini, Anatomical substrates of auditory selective attention: Behavioral and electrophysiological effects of posterior association cortex lesions, Cogn. Brain Res. 1 (1993) 227–240.
[71] S.H. Woodward, W.S. Brown, J.T. Marsh, M.E. Dawson, Probing the time-course of the auditory oddball P3 with secondary reaction time, Psychophysiology 28 (1991) 609–618.
[72] H. Yabe, M. Tervaniemi, K. Reinikainen, R. Näätänen, Temporal window of integration revealed by MMN to sound omission, NeuroReport 27 (1997) 1971–1974.